INITIAL SITE CHARACTERIZATION ENHANCED WITH GEOPHYSICS – A MULTI-BENEFIT CASE HISTORY AT A PETROLEUM UST SITE

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Abstract

A truck stop facility, located near Clayton, Indiana, has been the focus of an Initial Site Characterization (ISC) required by the State of Indiana for Leaking Petroleum Underground Storage Tank (LUST) sites. Conventional drilling-only assessment techniques by previous investigators were found to be inadequate at this site for developing an understanding of contaminant movement and distribution. The contaminants, principally gasoline and diesel fuel products, had been found widespread across much of this nine-acre site. In addition, the contaminants were found unexpectedly distant from known UST locations, in apparent conflict with the geologic setting which consists of compact, low permeability glacial till, typical of central Indiana. It was clear that anthropomorphic features such as utility trenches were somehow closely tied to contaminant movement.

Electromagnetic conductivity (EM-31 and EM-39), 2-dimensional electrical resistivity and ground penetrating radar were effectively used to reveal the sources of contaminant movement and to map out the contaminant transport network. This network consisted of narrow, interconnected pea gravel-filled drainage trenches crosscut by utility trenches. After initial discovery of the trenches with terrain conductivity mapping (EM-31), several detailed techniques were employed to further characterize and pinpoint these trenches. These small targets, generally less than two feet in width, were better defined by mapping the ratio of the EM-31 vertical dipole conductivity to horizontal dipole conductivity. Pinpointing of the trench locations and routes, critical to placement of boring locations and to the understanding of the flow network, was accomplished by an unconventional use of the Geonics EM-39 downhole conductivity probe as a surface-mapping tool and by using a Sensors and Software Noggin 250 ground penetrating radar system. An additional potential benefit to the EM-31 survey was the possible correlation of electrical conductivity with the degradation of petroleum hydrocarbons, consistent with similar recent findings by others.

Introduction

A nine-acre truck stop facility, located near Clayton, Indiana, approximately 25 miles west of Indianapolis (Figure 1), has been the focus of an Initial Site Characterization (ISC) (Mundell and Associates, 2001). The ISC is intended to provide accurate characterization of sites and delineation of impacts from leaking underground storage tanks. The Indiana Department of Environmental Management requires an ISC for all leaking underground storage tank (LUST) sites. Initial investigation activities, consistent with standard practice, consisted of soil borings and monitoring wells positioned based on analytical testing results and by the investigator's site knowledge (Creek Run, L.L.C., 1998a, 1998b, 1999).

Figure 2 illustrates the site layout, boring and well locations and understanding of contaminant distribution prior to the inclusion of geophysical techniques. The general topography of the site slopes from a high area in the west to a low wet area along the eastern edge of the site. The primary concern of the earliest investigation was to determine the extent of the impact the site has had on the property

Figure 1. Location map showing site near Clayton, Indiana

adjacent to the east. To this end, many of the initial borings are located along the eastern edge of the site. Scattered borings across the site indicate a large area of the site had been impacted by gasoline and diesel fuel (indicated in blue on Figure 2) with small areas (indicated in red on Figure 2) of identified separate-phase hydrocarbon on the groundwater surface. While the initial investigations provided an understanding of the impacts to the adjacent property, they did not provide an understanding of the mechanism of transport of the petroleum nor did they clearly identify the source of the petroleum release. One of the most puzzling results of the initial investigations was the discovery of gasoline impacts in soil and groundwater over 100 feet cross-gradient of the nearest gasoline UST installation.

This facility began operations in 1970 and had been agricultural land prior to the current operation. Small-scale historic releases of diesel and gasoline were known to exist dating back to about 1980. Faced with a larger UST site than typically encountered, the initial activities of the preliminary investigators were unsuccessful in adequately explaining the distribution pathways of diesel and gasoline in the soil and groundwater. High concentrations of both gasoline and diesel product were found widespread, several hundreds of feet distant from the nearest known underground storage tank areas, a confounding and unexpected circumstance in the compact, low permeability glacial till soils found in central Indiana.

Interviews with knowledgeable site personnel familiar with the early history of the site suggested that drainage trenches might have potentially contributed to the contaminant movements across the site. These trenches were reportedly installed during the initial site construction to drain near surface water away from the paved areas of the site. However, since no written documentation was available describing the drainage trenches, a means of mapping drainage trenches and other utilities was required. For this purpose, a geophysical investigation was considered appropriate. It was determined that the preliminary effort would comprise a terrain conductivity survey to detect the presence of trenches, assuming measurable contrast would exist between the electrically conductive glacial till and the more resistive coarse trench backfill.

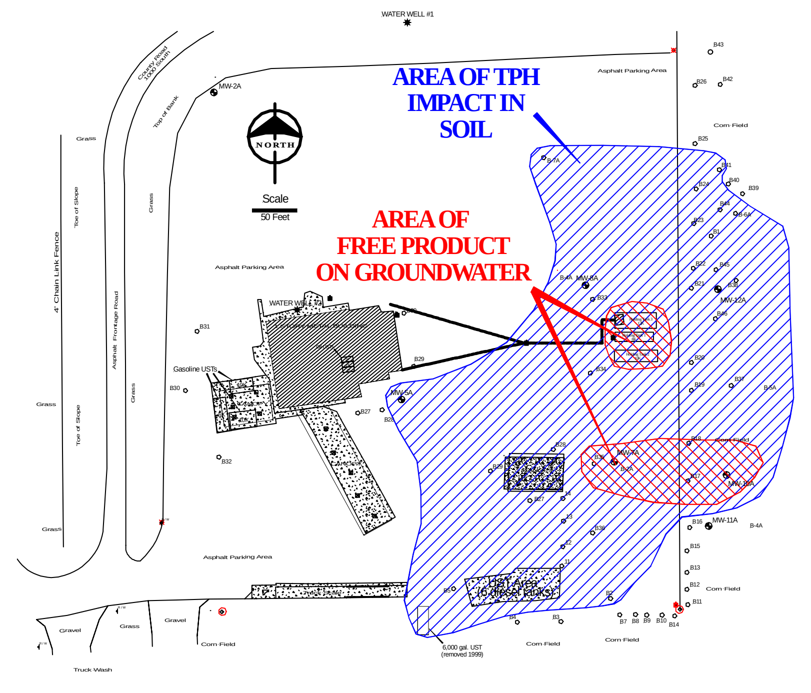

Figure 2. Map showing understanding of site conditions prior to geophysical survey (Creek Run, L.L.C., 1998a, 1998b, 1999). Blue cross-hatched area represented the extent of petroleum hydrocarbon impacts. The size of the contaminated area and its distance from the UST areas (on the south and west sides of the site) were difficult to explain given the impermeable soils.

Thus, the key objective of the terrain conductivity survey was to map variations in electrical conductivity across the site to identify possible buried drainage trenches and utilities. No geophysical testing had previously been conducted at this site, and the trenches had not been directly observed to establish their precise nature. However, based on recollections of those interviewed, the target of primary interest was believed to be relatively electrically resistive, unsaturated, pea-gravel filled trenches with cross-sectional dimensions of about two feet wide and five to six feet deep. Overall, the trenches were believed to be primarily aligned in a north-south orientation leading to an unknown discharge point (although diagonal or east-west connectors could also be expected). As such, the goal was to quantify shallow electrical conductivity in a nearly continuous manner over the area of interest. The data collection method was intended to maximize the north-south bias believed to be present.

Beyond mapping the contaminant pathways, another goal of the terrain conductivity survey was the mapping of variations in soil and fill types and to observe possible increased electrical conductivity effects caused by the presence of degrading petroleum hydrocarbons. This effect has been documented in recent work at a comparable geologic setting at a refinery site in Kalamazoo, Michigan (Abdel Aal et al., 2001).

Site Geology and Hydrogeology

The site, which is located in Hendricks County, Indiana, is situated within the southern part of the physiographic region known as the Tipton Till Plain. Most of the county is underlain by a thick assemblage of glacial drift deposits deposited on a strongly dissected pre-glacial landscape formed on bedrock of highly variable resistance to erosion. The thickness of Wisconsinan glacial drift, which is comprised of loam till of the Trafalgar Formation and some outwash, ranges from 50 to 100 ft in the vicinity of the site. The bedrock subcrop beneath the glacial drift consists of Mississippian age siltstone and shale with minor sandstone and discontinuous limestone of the Borden Group.

This site is located in the central portion of the White River Drainage Basin. The principal unconsolidated aquifers in the White River basin are associated with the glacial drift and outwash deposits along major rivers. However, the uppermost water-bearing formation beneath the site is a semiconfined, silty, clayey sand to a depth of about six feet below ground surface. Shallow, perched groundwater in monitoring wells and soil borings has typically been observed to be between 0.5 and 10.0 feet below the ground surface. Shallow groundwater flow generally follows the ground slope toward a wet area on the east edge of the site. The horizontal gradient of the shallow groundwater is generally in the direction of regional groundwater discharge, which is also to the east and southeast in the area.

Technical Approach

In this investigation, the initial geophysical method used consisted of an extensive terrain conductivity survey (Geonics EM-31). Flexible, rapid data collection with no need for ground contact made terrain conductivity a good choice for mapping shallow conductivity at this site, which is an active truck stop which is completely covered with asphalt pavement materials. The goal of this initial survey was primarily to test whether or not the drainage trenches could be observed reliably with geophysical methods.

Once it was determined that terrain conductivity was successful in imaging the drainage trenches, there was interest in further characterizing the trenches and surrounding soils and pinpointing the trench locations prior to drilling. Thus, several secondary geophysical methods were tested in a detailed study area after the terrain conductivity data were processed and preliminarily interpreted. These methods were intended to provide additional details about the nature of the trenches and the subsoils and to pinpoint the locations of the trenches prior to drilling soil borings. The secondary geophysical methods tested consisted of 2-dimensional resistivity imaging, an unconventional use of the

Geonics EM-39 conductivity downhole logging probe as a surface profiling tool, and ground penetrating radar.

The final step of this investigation was the implementation of the chosen secondary methods to complete the mapping of the drainage trenches. The use of ground penetrating radar was expanded across the entire site as this proved to be an excellent method for pinpointing the trench locations with the guidance of the EM-31 mapping for context. The geophysical data were also calibrated, or "ground-truthed", during the drilling phase of the project by comparing the results of downhole geophysical logging with the description of soil samples at several key locations.

Preliminary Site Mapping - Terrain Conductivity Method

Terrain Conductivity Method

The measurement of electrical conductivity to map geology has been utilized for over half a century, traditionally done with galvanic resistivity measurements through cumbersome electrode and wire sets requiring a significant amount of setup time. Electrical conductivity, or resistivity, has been demonstrated to be closely tied to geologic parameters as well as geochemical attributes of soil and groundwater, and a greater degree of variability is generally found in the conductivity, or resistivity, of geologic materials than any of the other fundamental physical properties. It was an awareness of the advantages of resistivity for engineering geophysical surveys combined with the laborious and slow pace of conventional resistivity techniques that led to the possibility of employing electromagnetic (inductive) techniques as an alternative for resistivity surveys. With electromagnetic conductivity meters, it is possible to map conductivity (inverse of electrical resistivity) relatively rapidly without making ground contact; furthermore, the sample volume is averaged in such a manner as to yield high resolution in conductivity.

For this project, the primary objective of the EM-31 survey was to obtain, in an efficient, cost-effective manner, conductivity (quadrature component) data within the shallow subsurface (down to about 5 feet) where possible drainage trenches and utilities are located. EM-31 data collection was conducted in two modes, vertical dipole and horizontal dipole, and the axis of the instrument was aligned in the north-south orientation for both coil orientation modes in recognition of the potential bias introduced by north-south trench alignments.

The choice of dipole orientation depends on the project objectives. The relative response of the EM-31 with depth is biased towards the near surface for the horizontal dipole mode, and is focused at a greater depth for the vertical dipole orientation. The EM-31 has a fixed intercoil spacing of 3.66 meters. In the horizontal dipole mode, the effective exploration depth is approximately 0.75 times the coil separation (i.e., about 9 feet), and for the vertical dipole mode the effective exploration depth is 1.5 times the coil separation (i.e., about 18 feet). Since the trenches were believed to be within the upper 5 to 6 feet of the subsurface, it was believed the horizontal dipole data would be much more strongly influenced by the presence of the trenches than the deeper-seeing vertical dipole mode. Further, it was surmised that mathematical comparison of the two coil orientations would more clearly reveal the trenches.

Positioning of the EM-31 was accomplished using a Trimble ProXR Global Positioning System (GPS) utilizing real-time differential correction with the Coast Guard Differential GPS (DGPS) Broadcast Data. The coordinates were tied to the site base map using several known points. Marking paint and survey tapes were used ahead of the EM-31 operator to maintain an approximately line spacing of 5 feet, but the EM-31 and differentially-corrected GPS data were collected simultaneously in real-time. These data were joined using a time stamp common to both data sets.

Terrain Conductivity Results

Surfer Version 7.02 surface mapping system (Golden Software, Inc.) was used to process and present the EM-31 conductivity data. The minimum curvature method was used to grid both conductivity data sets with a cell size of 1 foot by 1 foot.

The contour maps of conductivity, both horizontal dipole (Figure 3) and vertical dipole (Figure 4), are presented as color-filled maps with the specific fill colors keyed to the natural range of variation for the soils (determined using statistical analysis of site-specific data). Outliers in the form of extremely low or high conductivity values caused by the presence of metallic objects (essentially unwanted signal) are intentionally visually muted as a gray scale scheme that brackets the natural color scheme.

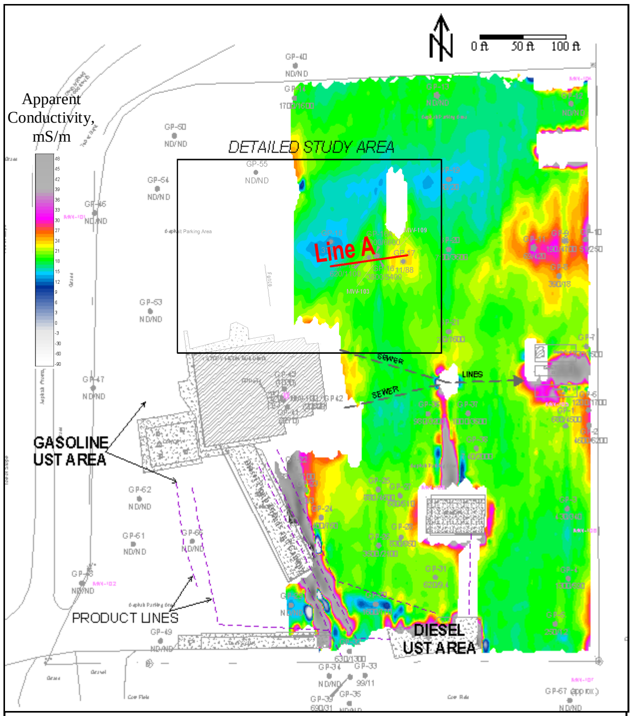

Figure 3. EM-31 Terrain Conductivity, Horizontal Dipoles. The instrument was aligned north-south.

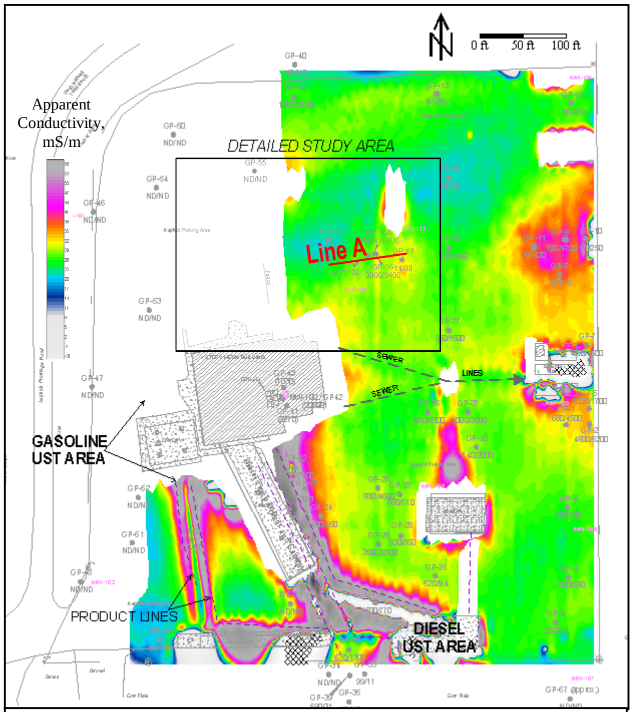

Figure 4. EM-31 Terrain Conductivity, Vertical Dipoles. The instrument was aligned north-south.

Review of each of the conductivity data sets indicated that the vertical dipole data values are, on average, a factor of approximately 1.4 times higher than the corresponding horizontal data. Thus, the color scheme for the vertical dipole is shifted by a factor of 1.4 relative to the horizontal dipole map to maintain relative color comparability in the natural range of soils.

Both EM-31 maps have similar general trends. There are several significant linear metallic features in gray tones including: the steel underground holding tanks at the center of the east side and product lines leading away from the underground fuel storage tanks on the south side of the site. The normal background level is depicted as green shading within most of the remaining areas surveyed. Normal background (green) coloration corresponds to a conductivity of about 16 to 21 mS/m (milliSiemens per meter) on the horizontal dipole map (Figure 3) and 22 to 30 mS/m on the vertical dipole map (Figure 4). The difference in normal range for the two maps suggests a vertical stratification, with the shallower (horizontal dipole) material being less conductivity than the deeper (vertical dipole). A few large, anomalous areas (non-metallic) are apparent as well. First, an anomalously low conductivity area is apparent in the northwestern portion of the study area (GP-18 and GP-19 are within the midst of this area). On the horizontal dipole map, this area is about 12 to 15 mS/m (blue to dark blue), or an anomaly of about 3 to 6 mS/m below background. Note the sharp northeast-southwest trending boundary on the eastern edge of this anomaly. On the vertical dipole map, this low conductivity anomaly is more subdued with a minimum of about 20 mS/m suggesting this is a shallow phenomenon since it is expressed more strongly on the horizontal dipole map.

On the east-northeast portion of the site is a significant high conductivity anomaly in yellow to magenta coloration (GP-9 is found within this area). The peak conductivity reaches about 44 mS/m and 32 mS/m on the vertical and horizontal dipole maps, respectively. This anomaly is about 18 mS/m above background at its peak. This anomaly could not be attributed to any known conductive metallic objects, and it appears instead to be related to conductive soils. Coincidentally, this is also an area highly contaminated with gasoline.

The drainage trenches were the primary subjects of interest, however, and these features would be expected to be elongated and very narrow (on the order of a few feet). Since the instrument was oriented north-south, the maps would be expected to be biased in favor of resolving north-south features. East-west features, although still detected, would be more subdued with lesser contrast and poorer lateral resolution. In addition, because the bottoms of the trenches are perhaps 5 to 6 feet in depth, the horizontal dipole map would be expected to most strongly reflect the low conductivity signature of a gravel-filled trench since the shallow subsurface has a greater influence on the horizontal dipole data (this would be particularly true where the gravel is dry). And, in fact a number of linear, north-south oriented low conductivity anomalies are apparent on the horizontal dipole map. They are more apparent in the northern half of the site, and, as confirmed by subsequent drilling, it turns out that greater portions of the drains are dry in the north. The drains in the southeast were found to be fully submerged, and thus less conductivity contrast is expected. Somewhat unexpectedly, at the locations where some of the most obvious linear low conductivity anomalies are found on the horizontal dipole map, we found linear *high* conductivity anomalies on the vertical dipole map. This suggested that a relatively conductive material was found at the bottom of the trenches. However, it did not seem likely that saturated pea gravel alone would be more conductive than moist silty clay. This is borne out on the horizontal dipole map on the southeast portion of the site. The submerged trenches, although completely saturated, were still low conductivity anomalies. At the bottoms of many of the trenches is an accumulation of hydrocarbons (weathered gasoline and diesel), leading to the suggestion that the degrading hydrocarbons may create an elevated conductivity.

In an effort to emphasize the presence of a narrow, linear fabric of the drainage trench anomalies, an additional processing step was conducted. The goal was to bring out the linear anomalies associated with the drainage trenches by subduing the broader variations in soil conductivity. In Surfer 7.02, the vertical dipole grid file was divided by the horizontal dipole grid file leaving a grid of values representing the ratio of vertical to horizontal dipole conductivities (V/H). This grid was contoured as a color-filled map, presented as Figure 5. On this map, a ratio of about 1.4 (light green color) represents "background" conditions, and the relatively narrow, linear zones (oriented north-south primarily, less prominent east-west) with a ratio between about 1.6 and 2.2 (dark blue to red color) correspond to the drainage trenches (the areas effected by metallic objects also appear to have high V/H ratios). The higher ratio corresponds to an anomalously low horizontal dipole conductivity relative to the vertical dipole conductivity, indicative of a higher resistivity material, i.e. pea gravel, in the shallow subsurface. The greatest ratio values tended to be where there was also a corresponding high conductivity anomaly in the vertical dipole. Interestingly, this also corresponded to locations where free product gasoline was often found in the trench bottoms and surrounding soils.

The V/H map (Figure 5) was much more successful in depicting the pattern of drains than either of the individual terrain conductivity maps. The north-south fabric is obvious, and there appears to be a significant diagonal drain leading to the northeast from the northeast corner of the building. The Y-shaped sewer line in the center of the site appears to be expressed in the data, although perhaps by a lower ratio than background, around 1.2. In general, however, east-west features are poorly defined, and it would appear to be necessary to conduct a second round of data collection with the instrument oriented east-west to successfully portray the east-west drains.

Although the preliminary EM-31 mapping proved indispensable in providing an understanding of the drain network, further site investigation activities and the proposed remedial corrective action plan demanded that the geophysical survey provide pinpoint accuracy as to the locations of the trenches. Drilling plans required that the drains be sampled, and concerns arose that not all drains were found by the EM-31 mapping, and that the resolution of the drain position was too imprecise with EM-31 alone. Using the EM-31 maps as a guide, investigation of more detailed methods was carried out as described in the following section.

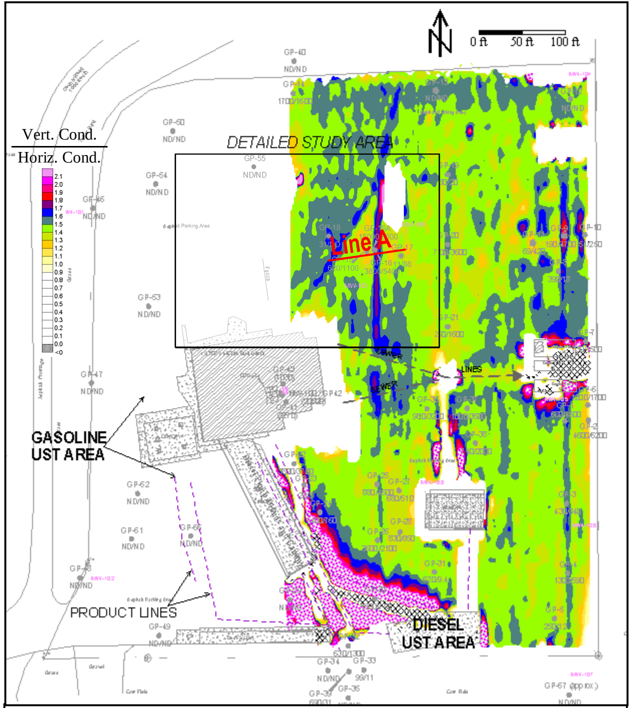

Figure 5. Ratio of Vertical Dipole to Horizontal Dipole Conductivity (V/H). Green corresponds to a ratio of 1.4 which is considered "background". Aside from the areas effected by metal objects, the elevated V/H values (blue to red) tended to correspond with areas backfilled with coarse material, particularly the linear drainage trenches.

Detailed Site Mapping

Resistivity Imaging

The electromagnetic conductivity mapping at the site provided an image of the lateral variations of bulk apparent conductivity. Apparent conductivity is essentially a composite image of the true subsurface conductivity. In a qualitative sense, depth relationships can be inferred by comparing the vertical and horizontal dipole conductivity data. However, the supposition that the drainage trenches were revealed by elongated, lower conductivity zones warranted closer scrutiny prior to drilling, particularly given the unexpected degree of variability of the electrical conductivity across the site. Thus, to add definition to the electrical conductivity structure of the shallow subsurface, one 2-dimensional electrical resistivity profile (i.e., cross section) was acquired perpendicular to one of the north-south conductivity anomalies assumed to be a trench. The location of this 88-foot profile, designated Line A, is shown on Figures 3, 4, and 5 in the detailed study area (red line).

The electrical resistivity instrumentation used for this project consisted of an Advanced Geosciences, Inc. (AGI) Sting R1 portable earth resistivity meter with internal memory storage. The Sting R1 was connected to an AGI Swift automated electrode switching system equipped with 30 switchable electrodes. The pole-dipole array type was chosen for this project because of its greater signal strength than the dipole-dipole array, and because it favors detection of lateral variations in resistivity. Since the pole-dipole is an asymmetrical array type, both forward and reverse data sets were collected. It was anticipated that this array would provide a high-resolution picture of the subsurface.

After the drilling of pilot holes at a spacing of two feet through the asphalt pavement, stainless steel electrode stakes were driven into the pavement base course material. Concentrated salt brine was needed to establish acceptable electrical contact with the subsoils at each of the electrode locations. All 30 switchable electrodes were connected to the electrode stakes that were laid out at 2-foot intervals, which resulted in an initial setup of 58 feet. A maximum "n" value of 6 was used to acquire of the pole-dipole pseudosection data. For the pole-dipole array, one of the current electrodes is fixed at a relatively far distance, and the remaining current and potential electrodes are moved. The fixed current electrode was laid out 120 feet west of the first electrode in the array in the "forward" setup, and then the fixed current electrode was then placed 120 feet east of the 30th electrode and data collection was repeated in a "reverse" setup. After completion of the data collection for the first pair of forward-reverse setups, one "roll-along" was performed in which electrodes 1-15 were placed east of electrodes 16-30, and the data collection cycle was repeated. The resulting composite pseudosection was 88 feet in length. The resistivity data were acquired with 2-dimensional data inversion in mind. Thus, The pseudosection was generated from the collection of 878 total lines of data.

The data were stored in the Sting R1 memory during acquisition, and then downloaded to a PC for inversion processing; in this particular case, RES2DINV Version 3.47e by Dr. Meng Heng Loke was used. An interactive process was used in the modeling of the 2D resistivity data with RES2DINV. Knowledge of general site characteristics, geologic setting, and resistivity characteristics of natural and man-made materials were incorporated in the process of evaluating the reasonableness of the modeling results. Based on soil boring logs from previous drilling, the geologic model used by the interpreter consisted of (from the ground surface down): 0.2 to 0.9 feet of asphalt, 0.15 to 0.5 feet of coarse gravel or limestone base coarse, 4 to 8 feet of silty clay (with occasional sand and gravel seams), followed by more than 8 feet of clayey silt (glacial till). This model also included the possibility of the narrow gravel-filled drainage trenches approximately 1 to 2 feet below grade to a depth of approximately 5 to 6 feet.

Once satisfactory calibration results were obtained with RES2DINV, the spatial coordinates and the model center block resistivity values were exported to ASCII delimited data file for plotting. The data were imported into Surfer Version 7.02 for final plotting as a color-filled cross section (lower portion of Figure 6). A simple triangular interpolation gridding method was used with a cell size of 1 foot by 1 foot. The resulting color-filled contoured cross section depicted the modeled electrical resistivity to a depth of about 10 feet.

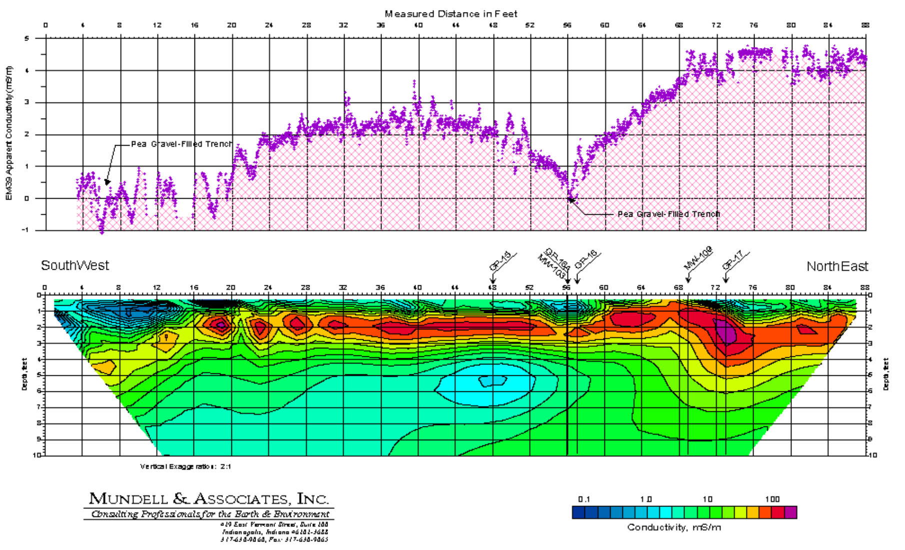

Figure 6. EM-39 (top) and 2-dimensional resistivity results (bottom) from Line A. Line A is found within the Detailed Study Area.

The resistivity cross section is in general agreement with the EM-31 results, as it reveals that there is an intermediate, albeit shallow, high conductivity layer at a nominal depth range of about 1 to 3 feet, and as much as 5 feet deep. The elevated conductivity corresponds to a clayey soil, below which is a dense clayey silt (glacial till). Above the conductive clay layer is a much less conductive material associated with the pavement material (crushed stone base course) and, at two locations, the drainage trenches. One trench, from about 0 to 16 feet horizontal position, appears to be very wide because it is a diagonally oriented (northeast-southwest) trench. The second trench is approximately located from about 53 to 58 feet. A confirmatory boring drilled at 56 feet (GP-16A) encountered about 5 feet of pea gravel, but a boring drilled at 57 feet (GP-16) found native soils highly impacted with gasoline. Although it provided visual confirmation of the subsurface structure, the 2-dimensional resistivity imaging proved to be too cumbersome and imprecise to be carried out site-wide.

EM-39 Profiling

Because of the relatively small size and extent of the trenches, a rapid, precise geophysical method was sought which could be used to pinpoint the locations of the trenches with a greater degree of certainty than afforded by the EM-31 or the 2-dimensional resistivity. Two methods were actually tested for this purpose, 1) the Geonics EM-39 downhole logging probe, used in an unconventional manner[1], and 2) ground penetrating radar (discussed in more detail below). Because the trenches were believed to be just below the asphalt pavement, the EM-39 was thought to be capable of providing a detailed look at the subsurface down to about a depth of approximately 3 feet (effective radius of exploration for this probe).

High resolution electrical conductivity profile data were collected with a portable Mount Sopris MGX-200 downhole logging system by pulling the EM-39 conductivity probe horizontally across the surface with the motorized winch on the MGX system. The logging probe was placed on a non-conductive skid (i.e., a cardboard box with duct tape) to protect it from abrasion, and was dragged across the ground at a “logging” speed of about 5 to 10 feet per minute. The probe was dragged across potential trench locations first identified by the EM-31. The starting and ending points of each profile were marked on the ground surface, and the intermediate positions of the profiles were precisely encoded in the data by the logging system. This allowed excellent positional control of the EM-39 data. The conductivity data were plotted against position. Figure 6 (upper graph), an example of one of these plots, was taken along the same transect as resistivity Line A, also shown on Figure 6 (bottom plot). The trench at the 56-foot position is a well-defined low conductivity anomaly. This plot also agrees very well with the upper 3 feet of the resistivity cross-section below it. As with the resistivity cross-section, the oblique crossing of the diagonal trench from 0 to 16 feet lead to a poor definition of the trench location there.

The EM-39 was found to perform its intended task well at locations where an obvious conductivity contrast was first revealed by the EM-31 survey, such as the anomalies apparent in the detailed study area. It was used successfully during the drilling investigation to pinpoint many of the trench locations. One problem encountered, however, was the high noise introduced by the presence of even trace amounts of metal on or in the pavement materials. These spurious data accounted for about 10 % of that collected along Line A (Figure 6); these data, generally of an extremely negative magnitude, were culled from the data presented on the graph. In some cases, the spurious effects of metallic objects obscured all useable data. Although not used on this project, a high-resolution conductivity meter such as the Geonics EM-38 would probably have been an excellent substitute for the EM-39 without the noise problems.

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[1] The EM-39 was used rather than more commonly used high-resolution conductivity instruments, e.g., Geonics EM-38, because of its immediate availability to the investigators.

Ground Penetrating Radar

The second method tested to help pinpoint the locations of the trenches was ground penetrating radar (GPR). A Sensors and Software Noggin 250 Plus system was used for this purpose. A standard, shielded 250-megahertz antenna was affixed to the Noggin Smart Cart. Data were collected using a 60-nanosecond total time window, four data stacks per trace, and a trace spacing of 0.16 feet. Figure 7 provides three examples of GPR profiles, the locations of which are shown on Figure 8 within the detailed study area.

GPR was the last method tested, and as the three GPR profiles in Figure 7 illustrate, GPR was successful in imaging the trenches. The trenches are revealed by a shallow “sag” or offset appearance, sharp trench edge diffractions creating an inverted “V” pattern, and, particularly in the case of the trench on Line 2, a strong train of multiples at the trench bottom (or top of water/free product?). This strong bottom reflection would be expected to result from a strong impedance contrast between the pea gravel and the underlying clay soil.

The Noggin Smart Cart system is well designed for rapid collection of GPR data, and allowed data collection and evaluation to be conducted in real time. This lead to the ability to pinpoint and mark the precise trench locations in the field in a manner similar to a typical utility locate project. As the trench locations were identified and pinpointed, their positions were marked periodically on the

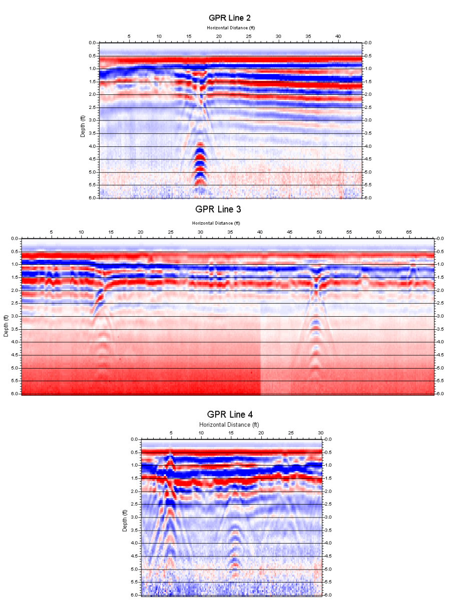

Figure 7. Example GPR profiles from the detailed study area. See Figure 8 for locations.

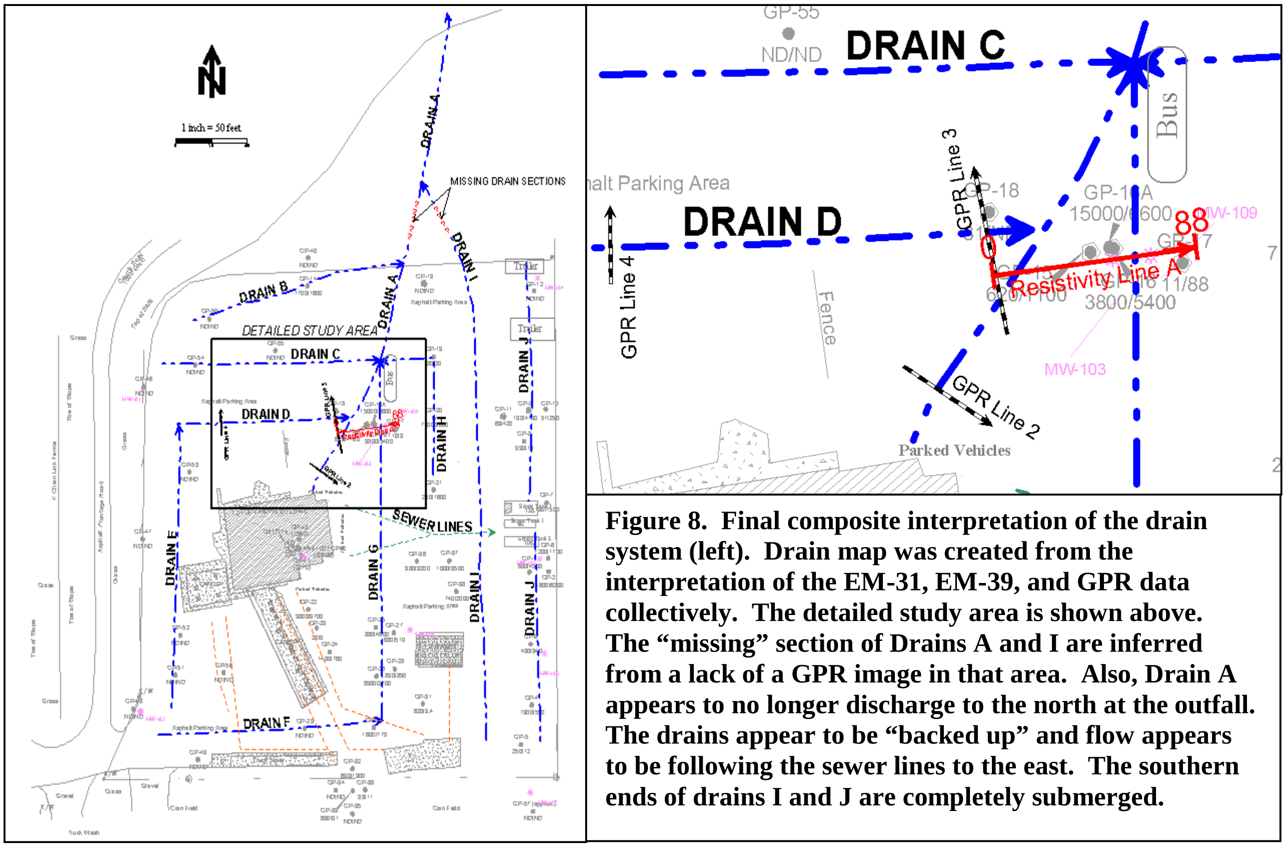

Figure 8. Final composite interpretation of the drain system (left). Drain map was created from the interpretation of the EM-31, EM-39, and GPR data collectively. The detailed study area is shown above. The “missing” section of Drains A and I are inferred from a lack of a GPR image in that area. Also, Drain A appears to no longer discharge to the north at the outfall. The drains appear to be “backed up” and flow appears to be following the sewer lines to the east. The southern ends of drains I and J are completely submerged.

ground surface with paint. Once the markings were made, GPS was used to locate the trenches on the site map. The GPR proved so successful in identifying the trenches that the entire trench system was mapped out within a single day. The final interpreted positions of the trenches are shown on Figure 8.

Summary and Conclusions

The primary purpose of conducting a geophysical survey at this site was to provide the primary investigators with the layout of the drainage trench network believed to have played a significant role in the migration of diesel and gasoline hydrocarbons across the site. Because the project included both the need to drill and sample the drainage trenches and surrounding soils, and to develop a remediation strategy for the site, it was also necessary that the trenches be located with a sufficient level of precision.

Initial terrain conductivity mapping using a Geonics EM-31 was successful in providing the broad framework of the drainage trench system, particularly the north-south drains. The added processing step of computing the ratio of vertical dipole to horizontal dipole conductivity was a useful tool for filtering out the broad conductivity variations and enhancing the view of the narrow drainage trenches.

Detailed mapping with ground penetrating radar following the EM-31 survey proved to be the most effective secondary method for precisely locating the trenches. In similar situations, it is apparent that the initial mapping with the EM-31 (or possibly an EM-38) followed by the detailed mapping and anomaly confirmation with ground penetrating radar would be an excellent combination of methods.

The drainage trench map that resulted from the geophysical survey (Figure 8) has proven to be an excellent basis for conducting further investigation work at this site and evaluating remediation costs for site cleanup. The map helped focus the scope of the confirmatory drilling and sampling activities. The sampling results have revealed by that the drainage trenches were crucial to the migration of hydrocarbons across the site. Many of the trenches on the east side of the site were subsequently found to contain residual, weathered hydrocarbons in the backfill material, and the adjacent soils were found to be highly impacted. This knowledge will be the foundation of the final hydrocarbon remediation at the site. By explaining the hydrocarbon distribution within the context of the network of drainage trenches, the actual volume of contaminated material that will be the focus of the source removal and treatment has been greatly reduced since most of the severe impacts border the trenches.

Finally, an effort was made to determine if the electrical conductivity data could be used as an approximate indicator of hydrocarbon impacts. As pointed out above, some of the areas of greatest contamination had greatly elevated soil conductivity, particularly in the northern portion of the site where the drainage trenches were not submerged. However, no clear, reliable correlation could be established directly between electrical conductivity and contaminant concentration. It is apparent that other chemical parameters besides the simple concentration of regulatory-driven organic compounds (such as benzene, toluene, ethylbenzene and xylenes in groundwater or total petroleum hydrocarbons in soils) likely play an important role in the relationship between electrical conductivity and organic contaminant distribution. Measurement of in-situ geochemical parameters (e.g., pH, dissolved oxygen, oxidation-reduction potential, specific conductance) in addition to the concentrations of selected organic acids and naturally occurring surfactants resulting from biodegradation of the primary petroleum hydrocarbon types should yield greater insight into this recently recognized phenomenon (Atekwana et al., 2000).

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